Bit Error Performance of Selected CCSDS Recommended Bandwidth Efficient Modulations Using the Block V Receiver

Dennis Lee[1] and Tsun-Yee Yan[2]

[1] *Jet Propulsion Laboratory M/S 238-343*
4800 Oak Grove Drive, Pasadena, CA 91109, USA
Dennis.K.Lee@jpl.nasa.gov

[2] *Jet Propulsion Laboratory M/S 238-343*
4800 Oak Grove Drive, Pasadena, CA 91109, USA
yan@arcadia.jpl.nasa.gov

INTRODUCTION

The increased congestion of space frequencies has brought about the necessity for advanced bandwidth efficient modulations. Such modulations often require complex receivers to provide optimal bit error performance. However, due to economics and other factors, many ground stations will not be able to upgrade their receiver capabilities in the near future to support these modulations. For this reason, missions using certain bandwidth efficient modulations (BEM) may not be able to obtain cross support from other space agencies still using older receivers. It is necessary to determine which bandwidth efficient modulations can be demodulated by current ground station receivers, and to quantify the losses due to a suboptimal mismatched receiver. We present the bit error rate measurements of six different bandwidth efficient modulations using the Block V receiver. The Block V receiver is the primary receiver deployed by NASA throughout the Deep Space Network (DSN).

The six bandwidth efficient modulations tested in this paper have been recommended by the Consultative Committee on Space Data Systems (CCSDS) for use in space-to-earth links in the Space Research Services bands (Category A 2200-2290 MHz, 8450-8500 MHz, and Category B 2290-2300, 8400-8450 MHz). Among the modulations recommended for Category A missions, we generated and tested Gaussian Minimum Shift Keying (GMSK) BT_b=0.25, Feher-patented Quadrature Phase Shift Keying (FQPSK-B), Square Root Raised Cosine Offset QPSK (roll-off factor α=0.5), and Butterworth filtered (BT_b=0.5) Offset OQPSK. We did likewise for GMSK BT_b=0.5 and trellis-coded Offset QPSK (T-OQPSK) which have been recommended for Category B missions. The recommended modulations meet the requirements of the SFCG (Space Flight Coordination Group) 17-2R1 spectral missions mask, and provide a narrow bandwidth and sharp spectral roll-off with reasonable bit error performance for a given E_b/N_o.

The study was divided into three parts. First, computer simulations were conducted using a OQPSK receiver model to demodulate the bandwidth efficient modulations. The simulation model incorporated integrate-and-dump detection filters, a crossover Costas carrier tracking loop, and a digital transition tracking loop (DTTL) for symbol timing acquisition and tracking. The second part of the study was the design of a digital waveform generator that could produce the baseband waveforms of the selected bandwidth efficient modulations. The design objectives of the waveform generator were low complexity and data rate capabilities up to 10 Mbps. A brief discussion of the waveform generator design is given, and the spectra and eye diagram of the modulations generated by the waveform generator are plotted. The final part of the study was to measure the bit error rates of the efficient modulations generated using the Block V receiver.

SIMULATED BIT ERROR PERFORMANCE

Computer simulations were performed using Signal Processing WorkSystem (SPW) software to determine the bit error rates of the six efficient modulations with an OQPSK receiver model. In addition to the six modulations mentioned above, two other recommended modulations from the CCSDS were also simulated. These modulations are SOQPSK-A and SOQPSK-B [1]. However, hardware bit error rate tests were not performed with these two modulations as they were introduced to the recommendation after the tests had been completed. A block diagram of the simulated OQPSK receiver is shown in Fig. 1. The carrier tracking is done with a crossover Costas loop, and the symbol tracking is done with a DTTL. The simulated additive gaussian noise channel included a model of a 10W ESA SSPA operating at full saturation. The AM/AM and AM/PM curves of the SSPA can be found in [6].

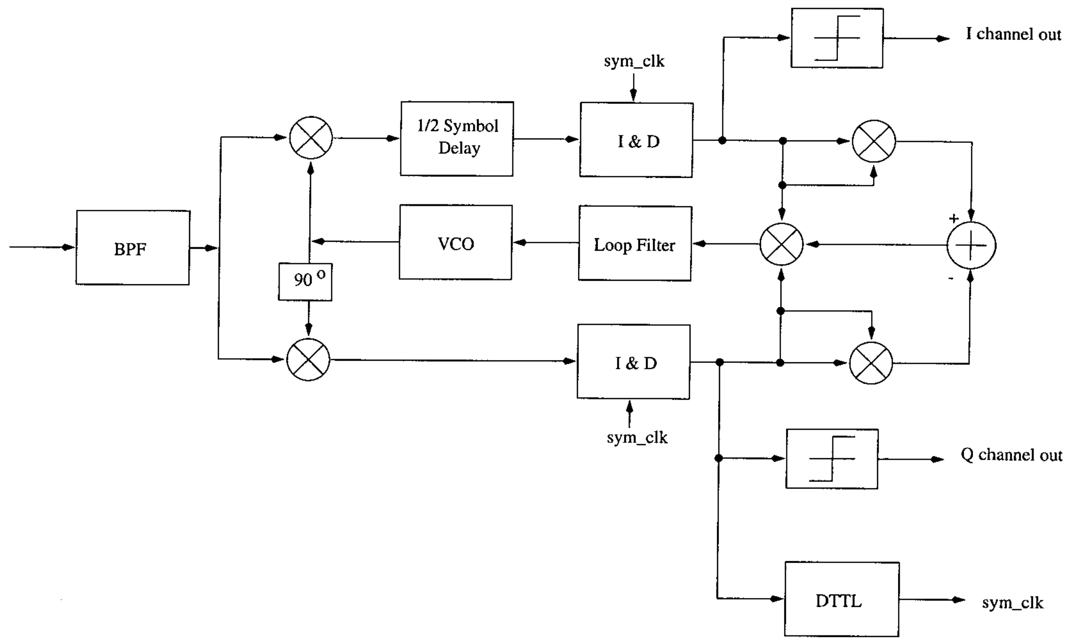

Figure 1: Block diagram of simulated OQPSK receiver

Fig. 2 shows the simulated bit error rates for the six BEMs with the OQPSK receiver model. Butterworth filtered OQPSK with $BT_b = 0.5$ has the least degradation with respect to ideal BPSK, approximately 0.6 dB E_b/N_o at 10^{-3} BER. The implementation losses using an OQPSK receiver at 10^{-3} BER for GMSK $BT_b = 0.25$ is 1.2 dB, 2.2 dB for FQPSK-B, 2.4 dB for SOQPSK-A, 1.4 dB for T-OQPSK, 1.1 dB for SOQPSK-B, 1.1 dB for SRRC OQPSK ($\alpha = 0.5$), and 0.8 dB for GMSK $BT_b = 0.5$.

Although these implementation losses are considerable, it should be noted that this is a direct result of using a mismatched receiver. For example, by modifying the detection filter the performance of GMSK $BT_b = 0.25$ and FQPSK-B can be improved by 0.9 dB [7] and 1.2 dB [4], respectively, at 10^{-3} BER. Additional simulation results [5] indicate that OQPSK receivers with detection filters modified for one of the efficient modulations can support the other modulations as well.

DESIGN OF DIGITAL BEM MODULATOR

In order to make hardware bit error rate measurements using the Block V receiver, a modulator had to built which could generate each of the efficient modulations. To this end, a design was created using a 100K gate FPGA (field programmable gate array) to generate different baseband waveforms using ROM lookup tables. These baseband waveforms were then modulated up to a 70 MHz IF (intermediate frequency) and then upconverted after some linear amplification to X-band. Testing done with T-OQPSK and GMSK BT_b=0.5 were performed with a different modulator using slightly different IF and RF frequencies.

The modulator design was based on an I-Q implementation using lookup tables to store the waveforms for each efficient modulation. Fig. 3 shows a block diagram of the waveform generator design for GMSK. A shift register is used to store the previous m incoming data bits, where m depends on the memory of the modulation. For SRRC OQPSK and Butterworth filtered OQPSK, the I and Q channel outputs are independent, and two separate parallel shift registers were used instead of one. The modulation output over a single symbol period was pre-computed for all possible combinations of length-m input sequences and stored in ROM tables, thereby accounting for the memory of the modulation and the ISI introduced by any pre-modulation filtering. Since both the Gaussian filter and SRRC filter used in GMSK and SRRC OQPSK respectively have an infinite impulse response and would theoretically require an infinite number of waveforms, it is necessary to window the impulse response to a finite length.

The two lookup tables in the FPGA block diagram shown in Fig. 3 are actually identical, with the values in the Q-channel

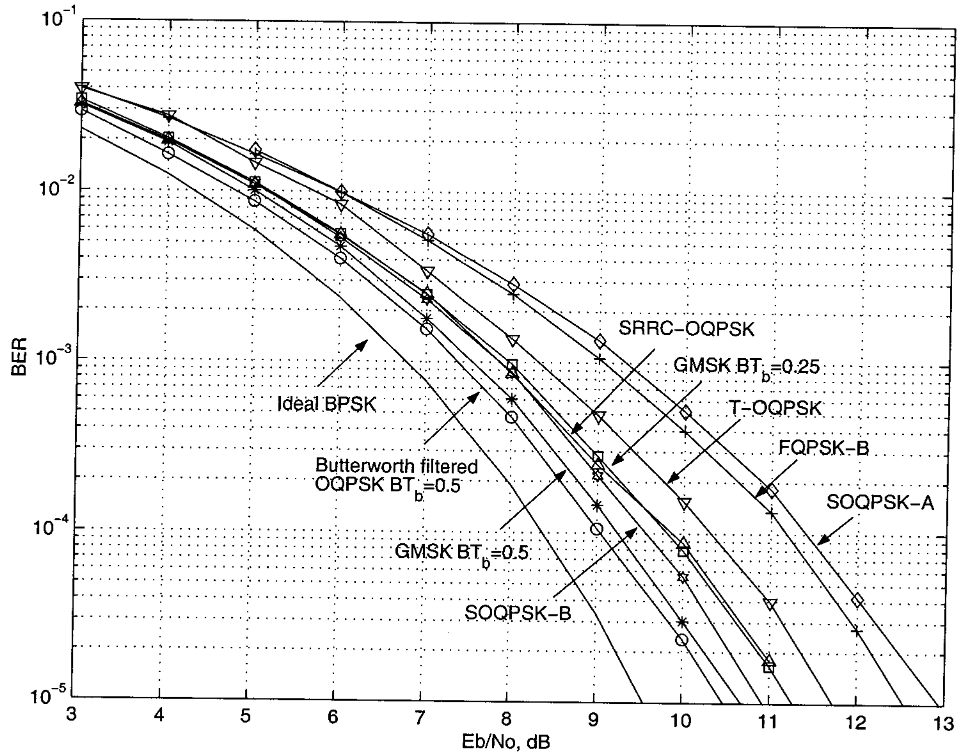

Figure 2: Simulated BER using OQPSK receiver

ROM shifted by half a symbol period to account for the offset in the inphase and quadrature phase channels. If space is a premium on the FPGA, only one table is required if a delayed version of the sample counter is used to clock the Q-channel ROM. In this implementation, Butterworth filtered OQPSK required only distinct two waveforms (just rectangular pulses) since the anti-aliasing filter after the DAC was a Butterworth filter and could double as the pre-modulation filter. FQPSK-B required 8 waveforms and T-OQPSK required 2 waveforms, while GMSK $BT_b = 0.25$, GMSK BT_b=0.5, SRRC OQPSK all needed 32 waveforms. Each full-symbol waveform consisted of eight 10-bit quantized samples. Further results [3] have shown that 8-bit quantization and 4 samples per symbol also provide acceptable results.

The advantage of using a digital modulator design based on ROM tables is that there is little computation involved in the FPGA since the waveforms have all been pre-computed. This avoids the need for multipliers and adders that would otherwise be needed in implementing the pre-modulation filter, and allows for faster processing and higher data rates with fewer gates in the FPGA design. However, as the size of the lookup tables grows exponentially with the memory of the modulation, it is only suitable for modulations with short memory.

Measured Eye Diagrams and Spectra

The eye diagrams of the bandwidth efficient modulations generated by the waveform generator were measured using an oscilloscope. Figs. 4a, 4b, and 4c show the eye diagrams of GMSK $BT_b = 0.25$, FQPSK-B, and Butterworth filtered OQPSK, respectively, at the output of the low pass anti-aliasing filter. Each horizontal division is 100 ns, and the bit rate in each case is 10 Mbps. To conserve space, the eye diagrams of the other modulations are not included but can be found in [5].

A spectrum analyzer was used to record the spectrum both after the linear amplifier at IF and after the saturated power amplifier at RF. Figs. 5a, 5b, 5c, and 5d show the linearly amplified spectra of FQPSK-B, GMSK $BT_b = 0.25$, T-OQPSK, and Butterworth filtered OQPSK, respectively. For comparison, Figs. 6a, 6b, 6c, and 6d show the non-linearly amplified spectra at RF of the same modulations. In these plots, all modulations were running at 10 Mbps and each horizontal

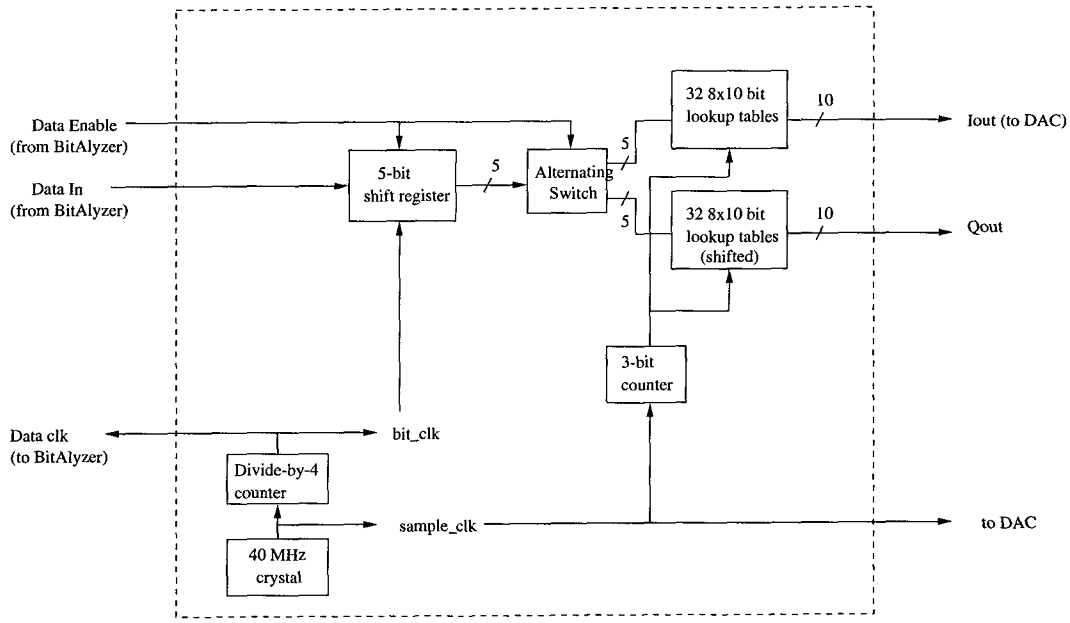

Figure 3: Block diagram for GMSK FPGA waveform generator

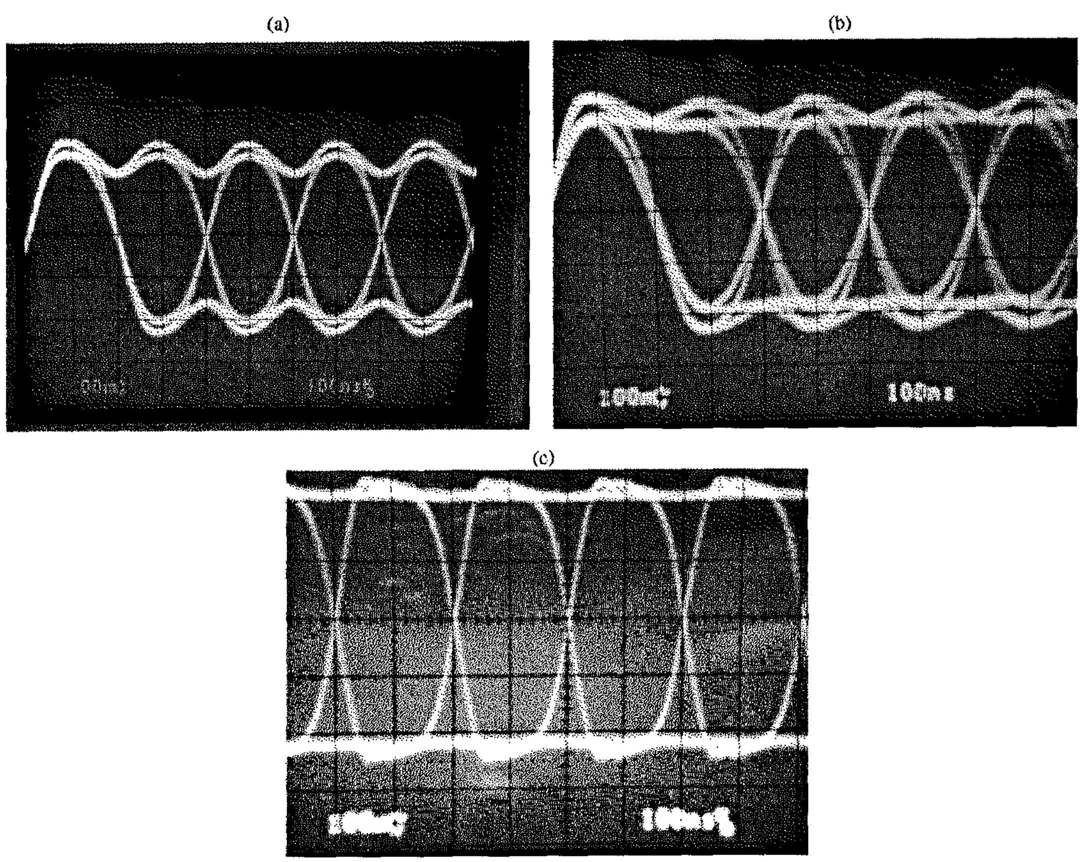

Figure 4: Eye diagram of (a) GMSK $BT_b = 0.25$, (b) FQPSK-B, and (c) Butterworth filtered OQPSK

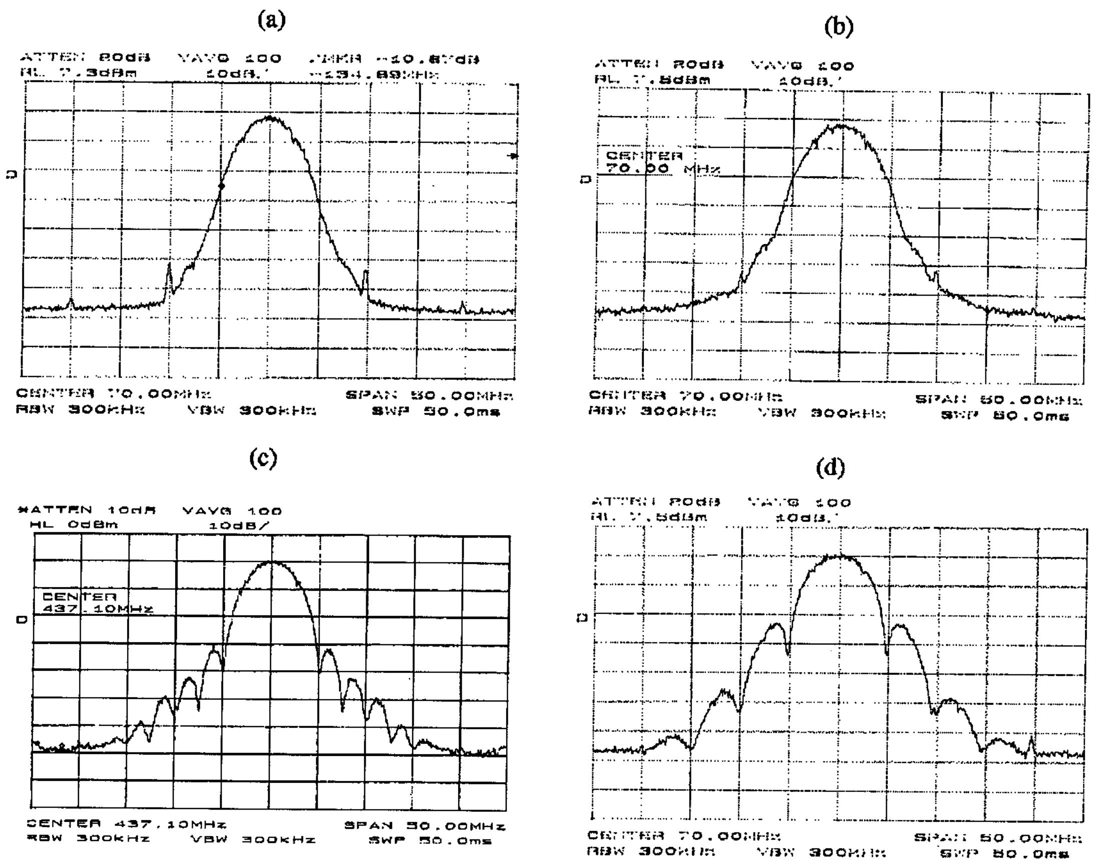

Figure 5: Spectra after linear IF amplifier of (a) FQPSK-B, (b) GMSK $BT_b = 0.25$, (c) T-OQPSK and (d) Butterworth filtered OQPSK

division is 5 MHz while each vertical division is 10 dB. Note that the spectra of GMSK $BT_b = 0.25$ and FQPSK-B are little changed following the saturated SSPA while T-OQPSK and Butterworth filtered OQPSK undergo some spectra regrowth. Again the measured spectra of the other modulations both before and after non-linear amplification can be found in [5]. GMSK $BT_b = 0.25$, FQPSK-B, SOQPSK-A, and SOQPSK-B had the narrowest spectra at the output of the saturated SSPA, while GMSK $BT_b = 0.5$, T-OQPSK, SRRC OQPSK, and Butterworth filtered OQPSK had comparatively wider spectra.

BLOCK V TEST SETUP AND BER MEASUREMENTS

The majority of Deep Space ground stations currently use the Block V receiver (BVR). The BVR [2] is capable of demodulating BPSK, QPSK, and OQPSK signals and supports fully suppressed carrier modulations. As the BEMs under consideration are inherently OQPSK-type modulations (i.e., staggered I-Q modulations), any receiver used for these modulations must be able to demodulate OQPSK. The BVR is a custom digital design which can handle data rates up to 26 Msps and can provide very narrow carrier and symbol tracking loop bandwidths for accurate tracking. In our tests, initial carrier acquisition was performed using a software FFT.

The bit error rate measurements were taken in the Telecommunications Development Laboratory (TDL) at JPL. A block diagram of the test configuration is show in Fig. 7. The FPGA waveform generator was clocked at 40 MHz, with 8 samples per symbol. At one sample per clock cycle, the I and Q channels each produced 5 Msym/s for a maximum rate of 10 Mbps. However, due to limited bandwidth of the interface to the Block V receiver, the BER tests were performed at 1 Mbps. A

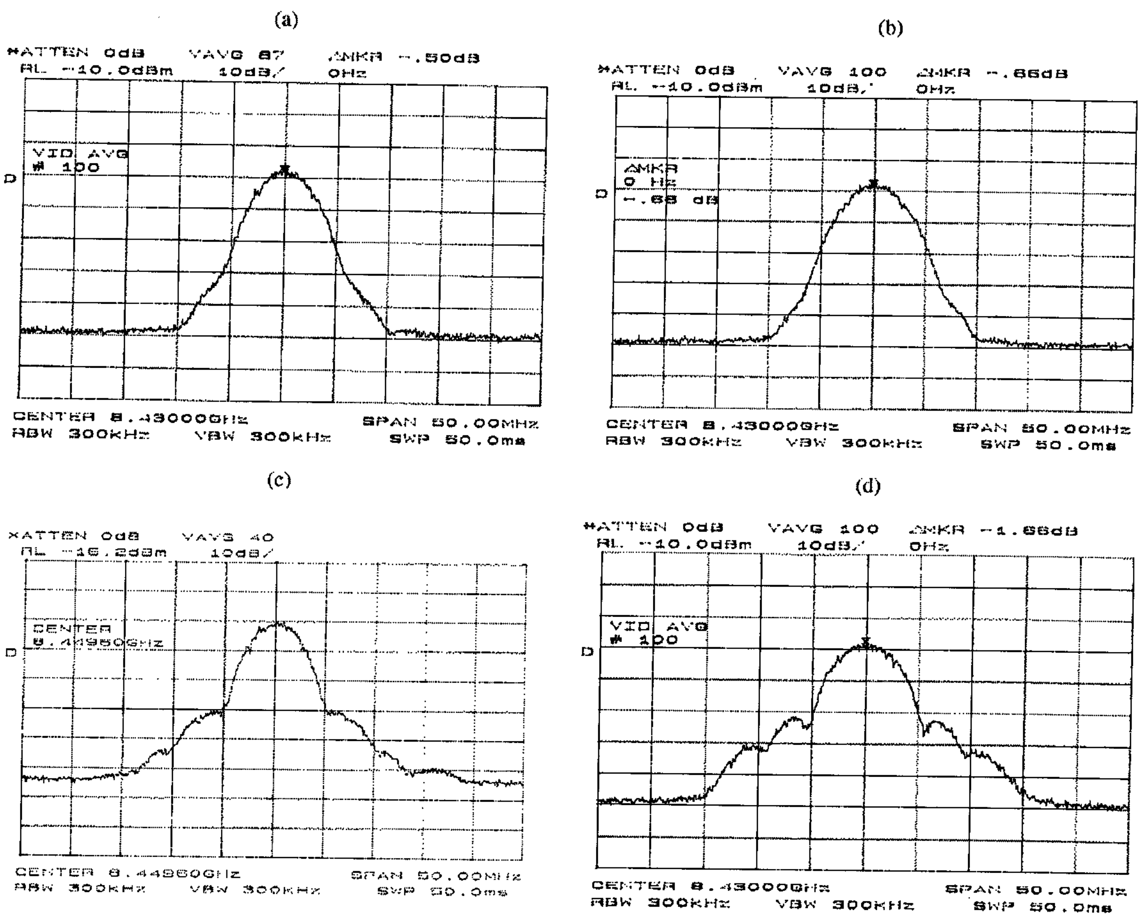

Figure 6: RF spectra at output of SSPA of (a) FQPSK-B, (b) GMSK $BT_b = 0.25$, (c) T-OQPSK and (d) Butterworth filtered OQPSK

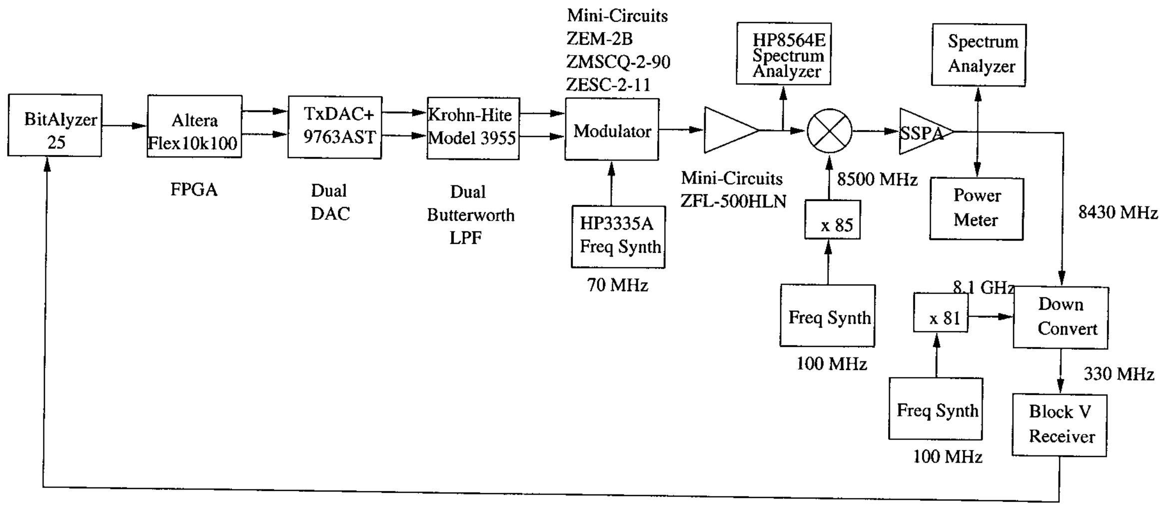

Figure 7: Test configuration

4th order Butterworth low pass filter was placed after the DAC to smooth the output of the DAC and to remove aliasing. After modulation to 70 MHz IF, the signal was linear amplified to provide enough drive power to saturate the SSPA. The signal was then upconverted to 8430 MHz and amplified using a 1 Watt X-band Miteq SSPA. For the T-OQPSK and GMSK BT_b=0.5 test which were performed at a later date, a 437.1 MHz IF and a 8449.6 MHz RF was used. Doppler and other channel imperfections were not considered in these tests.

Fig. 8 shows the measured BER using the Block V receiver to demodulate GMSK $BT_b = 0.25$, FQPSK-B, SRRC OQPSK, Butterworth filtered OQPSK, T-OQPSK, and GMSK BT_b=0.5. The measured BER performance of BPSK using the BVR is also shown as a reference. As indicated by the simulation results, Butterworth filtered OQPSK $BT_b = 0.5$ had the least BER degradation using the BVR, approximately 0.6 dB E_b/N_o from measured BPSK at 10^{-3} BER. The losses with respect to measured BPSK at 10^{-3} BER for GMSK $BT_b = 0.5$ is approximately 0.8 dB, 2.3 dB for FQPSK-B, 1.6 dB for T-OQPSK, 1.4 dB for GMSK BT_b=0.25, and 1.3 dB for SRRC OQPSK. Again, it should be emphasized that the large implementation losses of the bandwidth efficient modulations are due to an intentional mismatch between modulation and receiver, and that the actual performance with a matched receiver is significantly better [7] [6].

SUMMARY

A three part study was conducted to determine the bit error performance of the recommended bandwidth efficient modulations in CCSDS recommendations 2.4.17A and 2.4.17B with existing ground station receivers such as the Block V receiver. In the first part of the study, computer simulations were performed using an OQPSK receiver model to demodulate and detect GMSK BT_b=0.25, FQPSK-B, SRRC OQPSK ($\alpha = 0.5$), Butterworth filtered OQPSK $BT_b = 0.5$, SOQPSK-A, SOQPSK-B, T-OQPSK, and GMSK $BT_b = 0.5$. It was found that Butterworth filtered OQPSK and GMSK $BT_b = 0.5$ had the lowest losses using an I&D receiver, on the order of 0.6 dB and 0.8 dB E_b/N_o respectively. The second part of the study consisted of building a modulator to generate the different efficient modulations to be used in the BER tests. Such a modulator was built with data rates up to 10 Mbps using an FPGA to generate baseband waveforms of the modulations. The FPGA design was based on lookup ROM tables which allowed for higher data rates and low complexity. Spectrum measurements of the generated BEMs were taken before and after non-linear amplification to show the spectra regrowth of the selected bandwidth efficient modulations. The final part of the study was to setup the Block V receiver to demodulate the bandwidth efficient modulations and conduct the BER tests. The generated BEM signals were non-linearly amplified using a saturated X-band SSPA. Measured bit error rates with the Block V indicate that all the tested modulations (i.e., GMSK BT_b=0.25, FQPSK-B, SRRC OQPSK ($\alpha = 0.5$), Butterworth filtered OQPSK $BT_b = 0.5$, SOQPSK-A, SOQPSK-B, T-OQPSK, and GMSK $BT_b = 0.5$) can be received with an OQPSK receiver. While the losses in some cases are high, it should be remembered that the modulation and receiver have been intentionally mismatched and that BER results with a matched receiver are much improved.

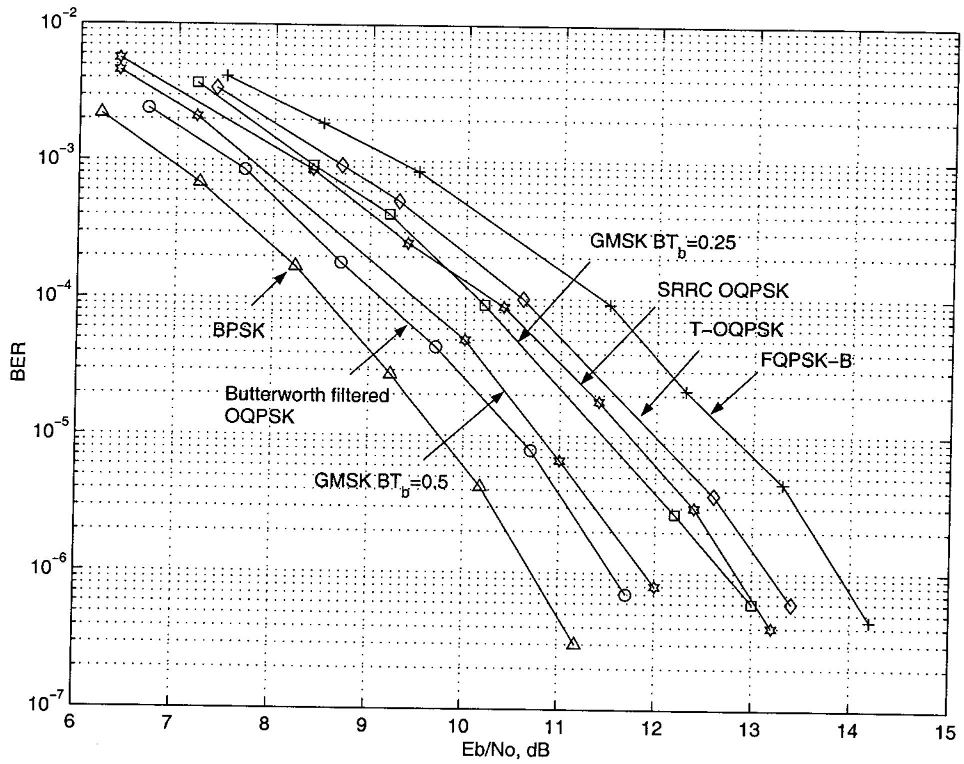

Figure 8: Measured BER using BVR

References

[1] T. Hill, "An Enhanced, Constant Envelope, Interoperable Shaped Offset QPSK (SOQPSK) Waveform for Improved Spectral Efficiency", Proceedings of 2000 International Telemetering Conference, pp. 126-136, October 2000.

[2] P.W. Kinman, "TLM-21 DSN Telemetry System, Block-V Receiver", 810-5 Rev. D, vol 1, December 1996.

[3] D. Lee, "Pre-coded GMSK Waveform Generation", JPL Interoffice Memo, August 29, 2001.

[4] D. Lee, "Improved Single Filter Detection for T-OQPSK and FQPSK-B", JPL Interoffice Memo, August 1, 2001.

[5] D. Lee and T.-Y. Yan, "Bit Error Performance of Selected Bandwidth Efficient Modulations using the Block V Receiver", JPL Interplanetary Network Progress Report, to be published.

[6] D. Lee and T.-Y. Yan, "Performance of Selected Bandwidth Efficient Modulations", CCSDS Panel 1E meeting, October 1999.

[7] G. Povero, E. Vassallo, and M. Visintin, "End-to-end Losses of Selected Bandwidth-Efficient Modulation Schemes", CCSDS Panel 1E meeting, October 1999.